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Numerical Simulation of Sediment Transport and Morphological Change of Upstream and Downstream Reach of Chi-Chi Weir

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1. Introduction

Chi-Chi Weir was built across a mountain river, Choshui River, in Central Taiwan (Fig.1). Because of the steep bed slope, abundant upstream sediment supply and tropical typhoon climate, the morphological changes are rapid in typhoon seasons. Since its operation in 2002, the upstream and downstream reach of Chi-Chi Weir had serious sediment problems: the storage of Chi-Chi Weir could be filled up in just one significant typhoon event, and the downstream reach had serious channel incision problem (Fig.2). According to the measurements in 2003, the averaged total annual amount of sediment yield is about 14.77 million m³ but only about 87% was transported to the downstream, and the capacity of the Weir loses about 1.92 million m³ in a year. For the downstream channel, the main channel composed of weak bedrock is scoured seriously. Deposition only occurred over the point bars. Fig.3 shows the difference of the bed elevation between 2007 and 2004; it is seen that all the main channel has been eroded with the thalweg being eroded more than 6 m.

To evaluate and predict the trend of morphological changes in natural rivers, a user-friendly and advanced two-dimensional mobile-bed model was needed. In this chapter, a computational model, CCHE2D, was adopted to simulate and investigate the sediment transport and morphological changes of upstream and downstream reaches near the Chi-Chi Weir. The study reach is from the upstream Chilun Bridge to the downstream Minchu Bridge. Transport of both suspended load and bed load sediment with multiple grain-sizes and non-equilibrium transport conditions were simulated. In addition, the incision mechanism of soft bedrock in the downstream reach of Chi-Chi Weir was considered in the model. Simulation results were calibrated and validated with the measured data. The long-term simulation of the morphological change, other than calibration and validation cases, was also studied within the reservoir and downstream reaches, respectively. However, the long-term simulation results are not shown here.

This collaborative study was executed among National Center for Computational Hydrosience and Engineering, USA, Water Resources Planning Institute, Water Resources Agency, and National Chiao Tung University, Taiwan (Yeh et al., 2008; Zhang et al., 2009).



Fig. 1. Upstream and downstream reach of Chi-Chi Weir, Choshui River, Taiwan



Fig. 2. (a) Channel incision in downstream reach; (b) Sediment deposition in upstream reach

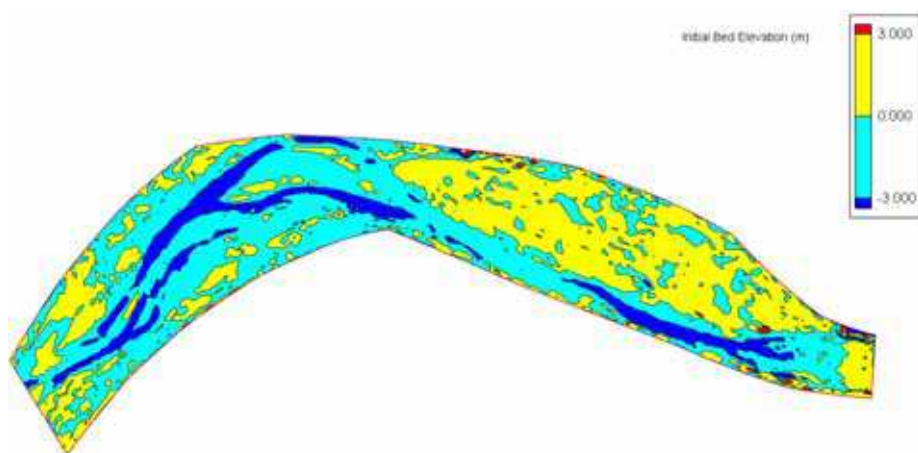


Fig. 3. Scouring and deposition pattern in the downstream channel of the Chi-Chi Weir (2004-2007)

2. Approaches

2.1 CCHE2D Hydrodynamic and sediment transport model

The CCHE2D model is a state-of-the-art numerical modeling system for two-dimensional, unsteady, turbulent river flow, sediment transport, and water quality prediction. The model is also designed for applications to multiple-process simulations in surface waters with complex geometry such as river bed and bank erosion with both uniform and non-uniform sediment and meander river migration. The model can be used for designing and evaluating the effects of the hydraulic structures, such as grade control structures, dikes, etc. The CCHE2D model uses a hybrid numerical method, the Efficient Element Method (EEM), which takes the advantages of both the Finite Element Method (FEM) and the Finite Volume Method (FVM). Depth-integrated two-dimensional equations (the continuity equation, the momentum equations, the k - ϵ turbulent equations, the sediment transport equations, etc.) are solved with multiple capabilities such as turbulent flow, wind-driven flow, tidal flow, and flow with vegetation effects (Jia and Wang, 1999, 2001a, and 2001b).

The CCHE2D model can simulate the transport of non-uniform sediment mixtures of multiple size classes with bed slope effects, secondary flow effect in curved channels, and avalanche effects. The capability of simulating the non-equilibrium sediment transport process is achieved by solving the following equations (Wu et al., 2000):

Suspended Load:

$$\frac{\partial (hC_k)}{\partial t} + \frac{\partial (UhC_k)}{\partial x} + \frac{\partial (VhC_k)}{\partial y} = \frac{\partial}{\partial x} \left(\epsilon_s h \frac{\partial C_k}{\partial x} \right) + \frac{\partial}{\partial y} \left(\epsilon_s h \frac{\partial C_k}{\partial y} \right) + a\omega_{sk}(C_{*k} - C_k) \quad (1)$$

Bed Load:

$$\frac{\partial (\delta_b \bar{C}_{bk})}{\partial t} + \frac{\partial (\alpha_{bx} q_{bkx})}{\partial x} + \frac{\partial (\alpha_{by} q_{bky})}{\partial y} + \frac{1}{L_t} (q_{bk} - q_{b* k}) = 0 \quad (2)$$

Bed Change:

$$(1 - p') \frac{\partial z_{bk}}{\partial t} = a\omega_{sk}(C_k - C_{*k}) + (q_{bk} - q_{b* k})/L_t \quad (3)$$

where h is the local water depth, U and V are the depth-integrated velocity components in the x and y directions, respectively; ϵ_s is the eddy diffusivity of sediment; C_k is the concentration of the k -th size class, and C_{*k} is the corresponding transport capacity; a is the adaptation coefficient for suspended load; ω_{sk} is the sediment settling velocity; $q_{b* k}$, q_{bkx} , q_{bky} are the bed load transport capacity, the bed load transport rate, and transport rate components in x and y directions, respectively; L_t is the adaptation length for bed load; p' is the porosity of bed material, and z_{bk} is the bed change.

The non-equilibrium adaptation length L_t characterizes the distance for a sediment process adjusting from a non-equilibrium state to an equilibrium state, which is related to the scales of sediment transport processes, bed forms and channel geometry.

2.2 CCHE2D bedrock model

The scouring of the bedrock is not a typical sediment transport problem because there are no sediment or bed materials on the rocky bed surface. A new capability has to be developed to handle this process. The research of Sklar and Dietrich (2001, 2004) is adopted, and a computer simulation module is developed to be integrated into the CCHE2D model.

Based on laboratory experiments, Sklar and Dietrich (2001) studied the process of bedrock abrasion by moving sediment particles. It was found that:

- The erosion rate decreases with the increase of the tensile strength of the bedrock.
- The erosion rate increases with the mass of the sediment particles; it will then decrease after a maximum value of the sediment mass rate has been reached. When sediment mass is low, its increase will add more particles to abrade the bed. After the maximum is reached, further increase of sediment will tend to cover the bed and thus reduce the erosion rate.
- The erosion rate will increase if the sediment particles are harder than the bed rock.

An empirical relation of the abrasion rate has been proposed later (Sklar and Dietrich, 2004), and it can be expressed as:

$$E = \frac{q_s w_{si}^2 Y}{L_s k_v \sigma_T^2} \left(1 - \frac{q_s}{q_t}\right) \quad (4)$$

where w_{si} = impact velocity of sediment particles (m/s), L_s = saltation length of sediment particles (m), q_s = sediment supply per unit width (kg/m/s), q_t = sediment transport capacity (kg/m/s), Y = Young's modulus of elasticity of bedrock (Pa), σ_T = tensile strength of the rock (Pa), and k_v = rock strength parameter (-).

The saltation length is expressed by an empirical equation:

$$\frac{L_s}{D_s} = 8 \left(\frac{\tau}{\tau_c} - 1 \right)^{0.88} \quad (5)$$

And it is modified with a factor to account for the effect that the particle hop length grows rapidly as shear velocity u_* (m/s) approaches the particle fall velocity, w_f (m/s):

$$\frac{L_s}{D_s} = 8 \left(\frac{\tau}{\tau_c} - 1 \right)^{0.88} \left[1 - \left(\frac{u_*}{w_f} \right)^2 \right]^{-0.5} \quad \frac{u_*}{w_f} < 1 \quad (6)$$

The saltation length becomes infinite when $u_* \rightarrow w_f$.

where τ = shear stress over the bed (Pa), τ_c = sediment critical entrainment shear stress, and D_s = sediment particle size (m). The impact velocity of sediment particles on the bed is formulated as

$$w_{si} = 2w_{sd} = 0.8 \left[\left(\frac{\rho_s}{\rho} - 1 \right) g D_s \right]^{0.5} \left(\frac{\tau}{\tau_c} - 1 \right)^{0.18} \left[1 - \left(\frac{u_*}{w_f} \right)^2 \right]^{0.5} \quad (7)$$

where w_{sd} = sediment particle descendent velocity (m/s), ρ_s, ρ = sediment and water density (kg/m³), and g = gravitational acceleration (m/s²).

It assumes that there is no erosion of the bedrock by rolling bed load sediment particles, and the sediments are totally suspended. These two assumptions are not fully consistent with the experiment and field observation that even clear water could erode the soft bedrock. In sediment transport research, the criterion, $u_* \rightarrow w_f$, is generally considered as the initiation of sediment suspension rather than the complete suspension.

3. Simulation of sedimentation process upstream of the Chi-Chi Weir

3.1 Mesh generation

A computational mesh (40 x 161) was generated using CCHE-MESH based on the measured cross sectional data in Oct. 2004. The measured cross sections are much finer in vertical resolution, which are more accurate and reliable than the DEM data, so the cross sections were used to interpolate the bed elevation for the computational meshes. Since the cross sections are not fine enough horizontally, special refinement treatment was performed for all the cross sections. The refinement is based on the interpolation between cross sections in the estimated flow direction. The mesh was extended about 140m upstream of Chilul Bridge (Fig. 4).

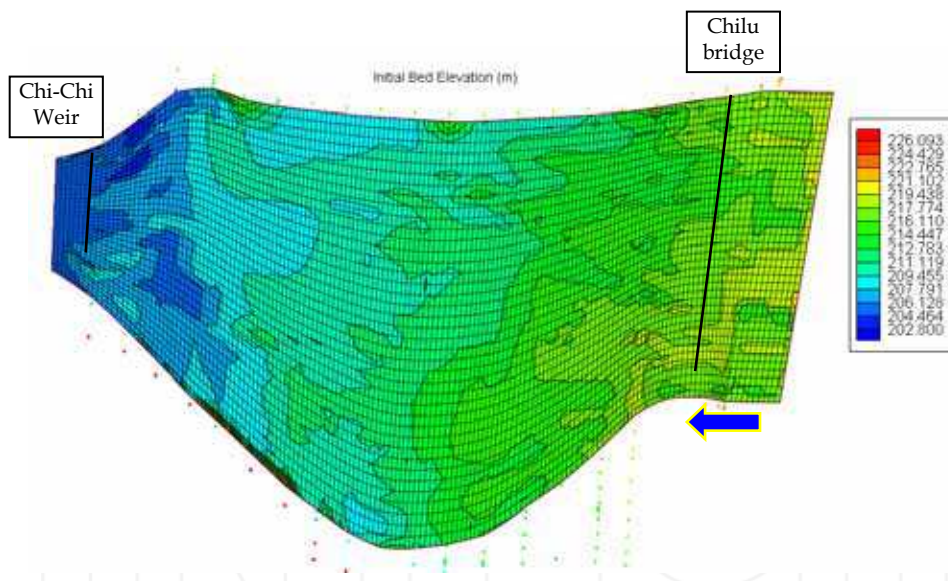


Fig. 4. Computational mesh with Oct. 2004's bed elevation as the initial condition

3.2 Bed material and grain size

Bed samples obtained in July 2004 are used as initial bed composition within the reservoir. Table 1 and Table 2 list the representative grain sizes, in this study six size classes were selected to simulate the sediment transport upstream of Chi-Chi Weir. The location of the bed samples within the computational domain is shown in Fig.5.

Size Classes (mm)	Lower Limit (mm)	Upper Limit (mm)
0.0272	0.001	0.074
0.297	0.074	0.59
2.38	0.59	4.76
9.52	4.76	19.1
152	19.1	305
457	305	610

Table 1. Size classes in model

Sample	Class-1	Class-2	Class-3	Class-4	Class-5	Class-6
1	0.28	0.72	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.14	0.41	0.45
3	0.00	0.00	0.27	0.215	0.465	0.05
4	0.00	0.00	0.11	0.12	0.40	0.37
5	0.00	0.00	0.17	0.16	0.47	0.20
6	0.00	0.00	0.15	0.115	0.395	0.34

Table 2. Compositions of bed samples

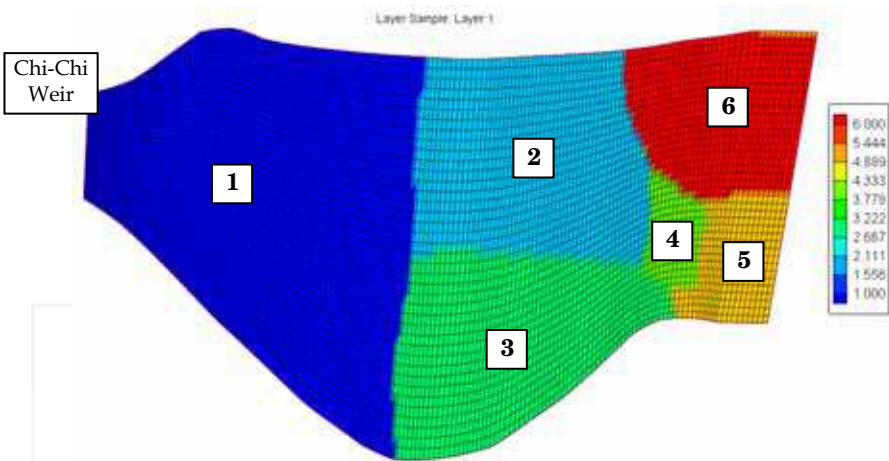


Fig. 5. Location of bed samples in July 2004

3.3 Boundary conditions

The typhoon events from August 2004 to June 2008 were selected to calibrate and validate the model (see Fig. 6). The sediment hydrograph data was obtained according to the relationship between the flow discharge and the sediment concentration. Since the Chi-Chi Weir is at the downstream boundary, the rating curve was used instead of stage hydrograph (see Fig. 7).

Although the suspended load transport is dominant within the reservoir, the bed load is also important. It assumed that there is a small amount of the bed load coming from upstream of Chilui Bridge. The bed composition data measured at CS 121 (Chilu Bridge) is considered as the composition of the bed load. The composition of suspended sediment at Chilui Bridge is shown in Fig. 8.

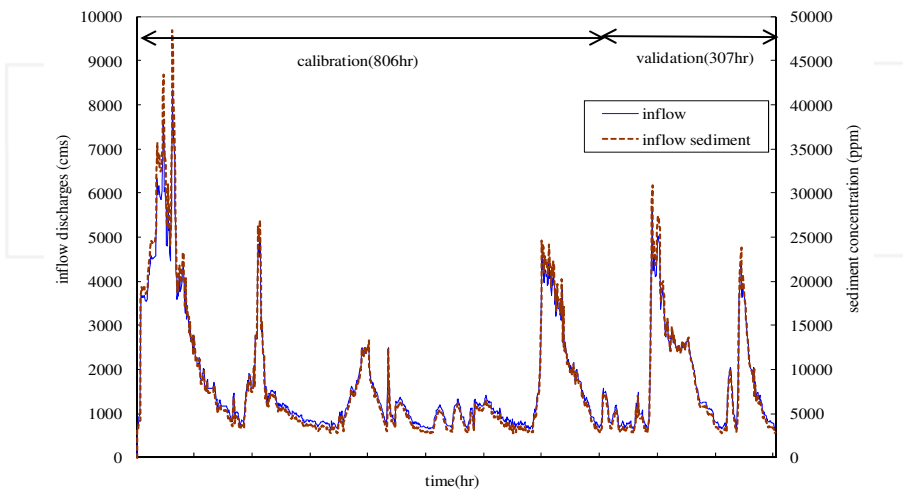


Fig. 6. Typhoon events from August 2004 to June 2008 (upstream boundary conditions)

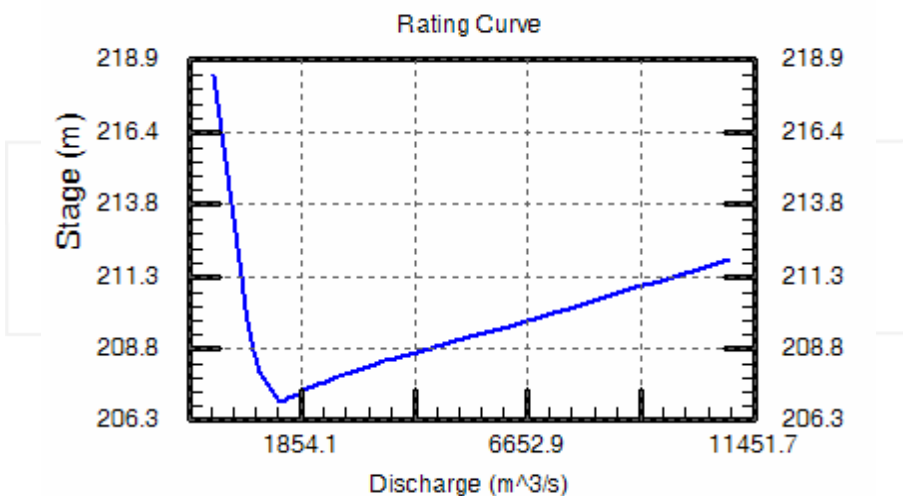


Fig. 7. Q-H rating curve at Chi-Chi Weir (downstream boundary condition)

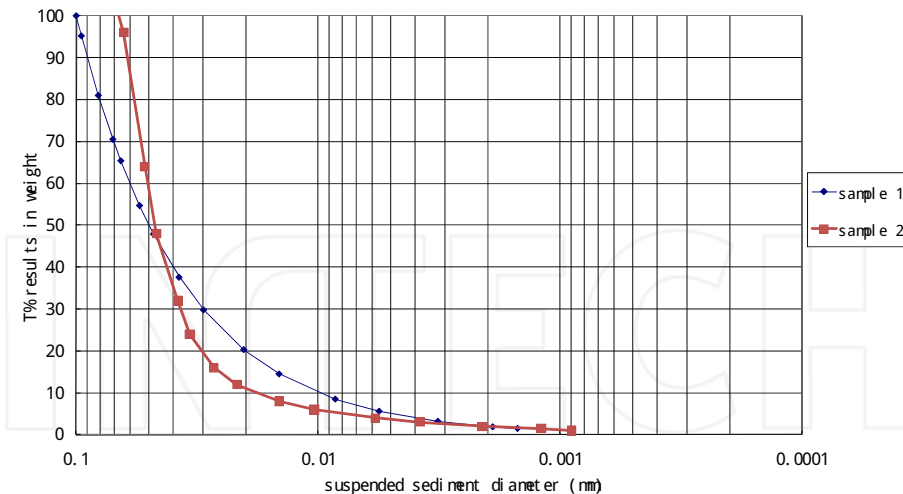


Fig. 8. Composition of suspended sediment at Chilu Bridge

3.4 Simulation results

The bed elevation was interpolated onto the computational mesh using the topographic data of Oct. 2004 and Jan. 2007, respectively. Fig. 9 shows the comparisons of the bed elevation change in this period (from 2004 to 2007). A large erosion area (A) was observed on the delta where deposition usually occurs, which was caused by extensive dredging in the simulation period. The delta with fine sediment extended further downstream toward the Weir site and formed two large depositions (B and C) which stopped a few hundred meters from the Weir. A scour hole (D) appeared immediately behind the Weir, which could be caused by three dimensionality of the flow and associated sediment transport.

The model was calibrated using the bed topography of Oct. 2004, the flow and sediment hydrograph from July 2004 to June 2006. Sensitivity studies were performed on the following main model parameters: (1) Ratio of bed load and suspended load (90% suspended sediment, 10% bed load; 95% suspended sediment, 5% bed load; and, 99% suspended sediment, 1% bed load); (2) Bed load adaptation length L_t (= 1000m, 1500m, 2000m, and 3000m); (3) Suspended load adaptation coefficient α (= 0.01, 0.015, and 0.02); and, (4) Bed roughness n (= 0.04, 0.032, and 0.025). According to the simulation tests, 95% suspended load and 5% bed load produced more reasonable results, and the combination of bed roughness, bed load adaptation length and suspended load adaptation coefficient (L_t = 3000m, α =0.01, and n = 0.025) produced the best results.

Fig. 10 shows the final flow field and the water surface level, and Fig. 11 shows the peak flow field and water surface level. When the flow discharge was low, large dry areas over the delta appeared. In the erosion zone A, the simulated results show slight depositions; in the deposition zones B and C, the model under-estimated the depositions; in the deposition zone E, under-estimated results were observed as well; the model predicted two scour holes instead of one in zone D; and, in deposition zone F, the simulation agrees well with the measurements.

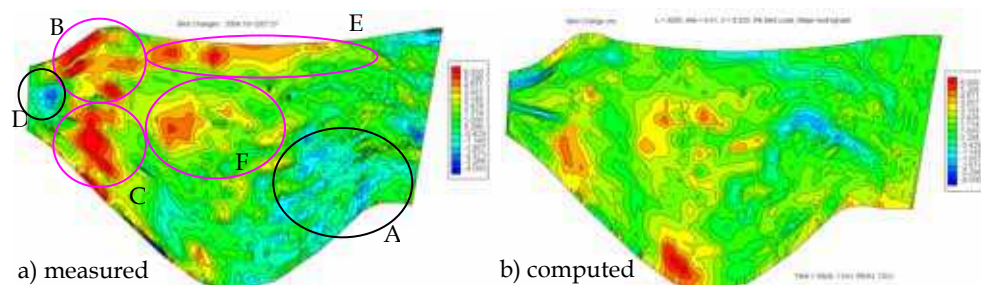


Fig. 9. Measured and computed bed changes

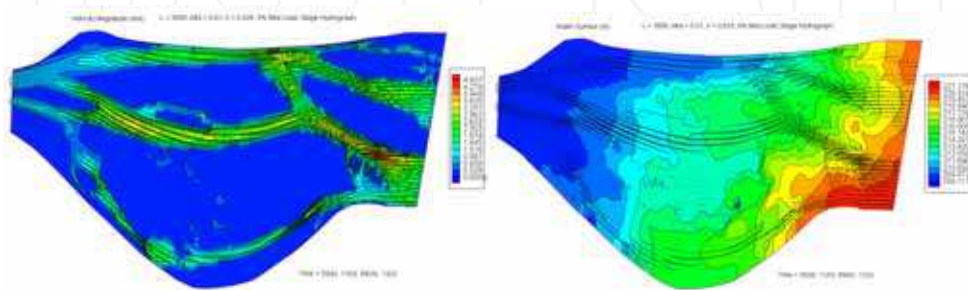


Fig. 10. Simulated flow field and water surface level

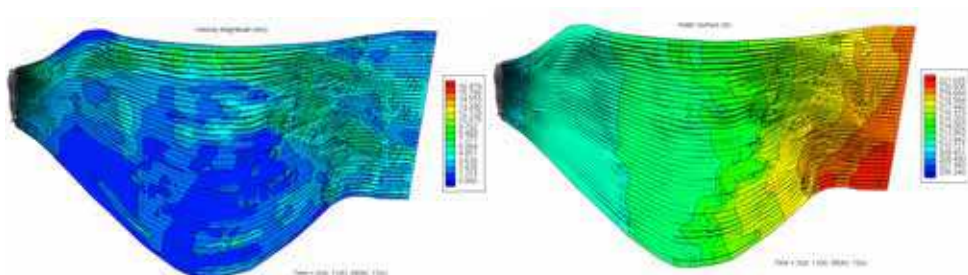


Fig. 11. Peak flow field and water surface level

Fig. 12 and Fig. 13 show the cross sections where the simulated bed elevations are compared with those measured in Oct. 2004 and Jan. 2007. For CS 1~4, the simulated results basically showed good agreements with the measurements except some small scour holes; for CS 5~10, the simulated results under-predicted the large erosions over the delta dredging area (zone A, Fig. 9); for CS 11~15, the simulation correctly predicted depositions, but underestimated near the right bank and over-estimated near the left bank; for CS 16~19, the simulated results under-estimated the depositions; and, for CS 20, the large scour hole in front of the Weir was not predicted well.

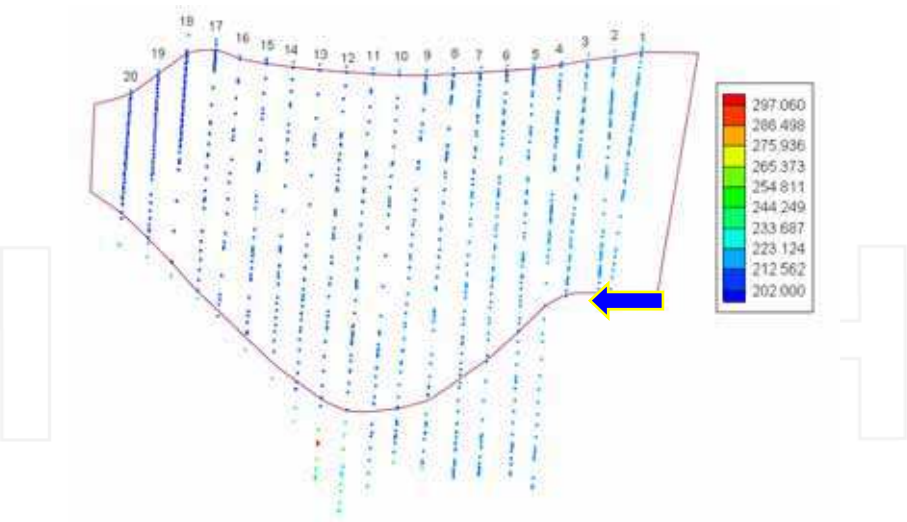
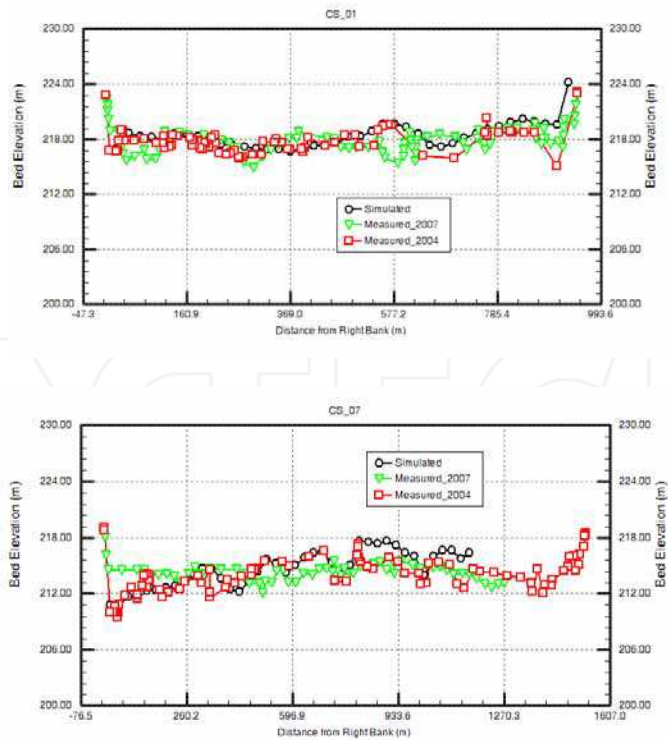


Fig. 12. Location of cross sections



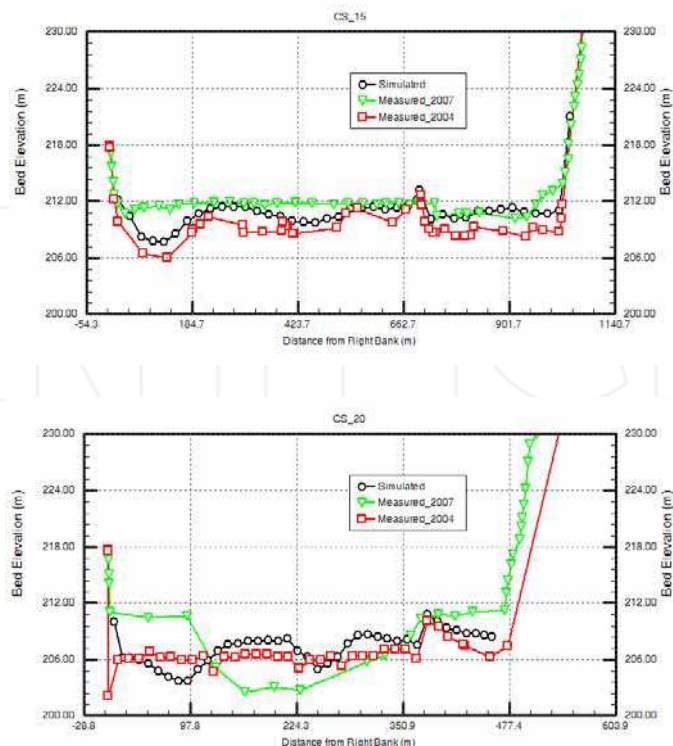


Fig. 13. Comparisons of cross sections

4. Simulation of the bedrock scouring process downstream of the Chi-Chi Weir

In the channel downstream of the Chi-Chi Weir, the bedrock channel has been eroded significantly. The scour depth has reached as much as 10 m. A field inspection indicated that the bedrock was covered by a thin layer of coarse bed material before the Weir's operation; the bedrock scour started after this layer of bed material was washed away. Fig. 14 shows the scoured bed, floodplain with thin armor layer and the point bars. The erosion is mainly concentrated in the main channel, and the point bars nearby has slight deposition. From the field inspection and photos taken in the past, there is no deposition over the bare bedrock. The flow and the sediment just pass over the bedrock bed, and result in channel incision.

The CCHE2D model was applied to simulate the bedrock scouring process. The same typhoon events from August 2004 to June 2008 as in the upstream study were selected to calibrate and validate the model. Since this is a site specific problem, new model capabilities have to be developed to handle the special need for rock scouring mechanism. A new computational module was developed and integrated into the CCHE2D model.



Fig. 14. Scoured channel bed downstream of the Chi-Chi Weir

4.1 Mesh generation

The cross sectional data in 2004 was used to generate the computational mesh, which was then used to simulate the flow, sediment transport and bedrock incision. A computational mesh (29 x 131) was generated using CCHE-MESH (Fig.15). The study reach was from upstream Chi-Chi Weir to downstream Minchu Bridge.

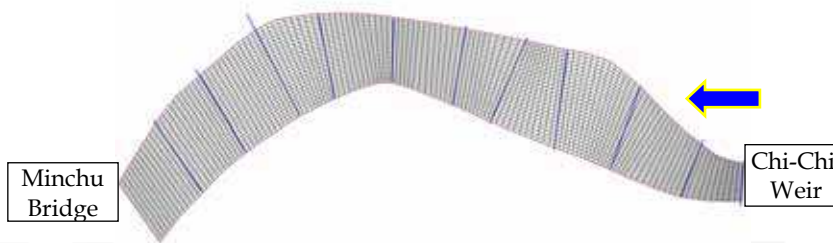


Fig. 15. Computational mesh in the channel downstream of the Chi-Chi Weir

4.2 Simulation results

Fig. 16 indicates the computed water depth in the channel overlaid with the velocity vectors. Due to the complex topography and the unsteady flow, a special wetting and drying treatment technique was used, and the mass conservation of the solution is good. This can be checked easily with steady cases by integrating the flow mass flux along the channel. In the areas where dry elements exist among wet ones, the mass conservation could not be preserved as good as in the mean channel. The influence of the dry-wet elements on the momentum conservation is similar to that on the mass conservation.

In Fig. 17, the measured and the computed bed elevation changes were compared. The overall pattern of bed change is similar to what has been observed. The bedrock channel incision pattern agrees with the data better than that of the deposition over the point bars,

because only flows with high peak discharges were able to pass over the floodplains. Apparently, the erosion rate of the bedrock in the channel downstream of the Chi-Chi Weir is substantially larger than those used in the experiment (Sklar and Dietrich, 2001, 2004). The developed bedrock erosion model and the calibrated model parameters were validated using the observed flows and estimated sediment loads in the period from Jan. 2007 to June 2008. It was assumed that 90% of the sediment entering the downstream channel was in the form of suspended load, and 10% was bed load. This ratio is the same as that used in the case of calibration. The simulated erosion over the bedrock ranges from 1.0 to 2.2 meters with the larger erosion appearing near the Weir site (see Fig. 18). The largest erosion (about 3.2 m) is very close to the Weir, but the associated eroded area is small.

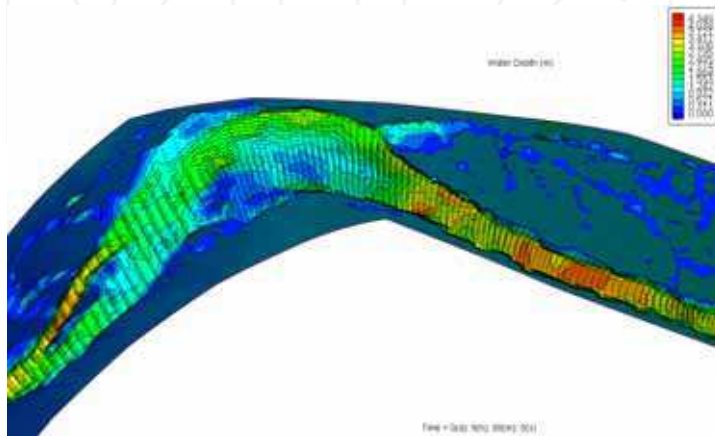


Fig. 16. Computed water depth and velocity field

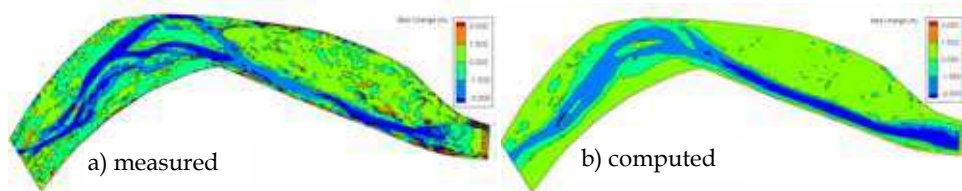


Fig. 17. Measured and computed bed changes (calibration case)

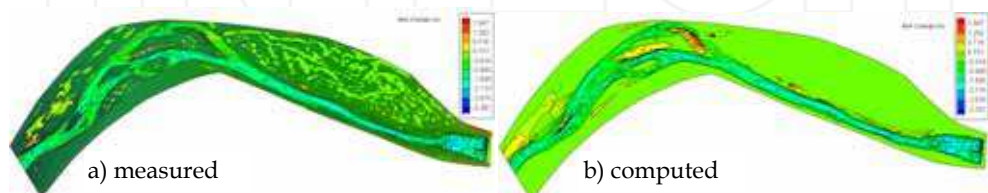


Fig. 18. Measured and computed bed changes (validation case)

Fig. 19 indicates the location of the measured cross sections. Fig. 20 compares the measured and computed cross sections. It can be seen that the simulation over-predicted erosion upstream of section 15, which might be due to the low horizontal resolution of the cross sectional data measured in 2008.

The agreement among sections 15 to 21 is better. Some cross sections agree well although the channel geometry and bed conditions are complicated. Downstream of the section 25, the calculation seems to over-predict the erosion somehow.

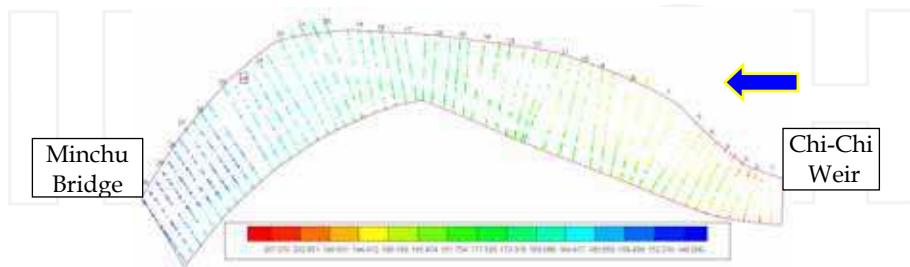
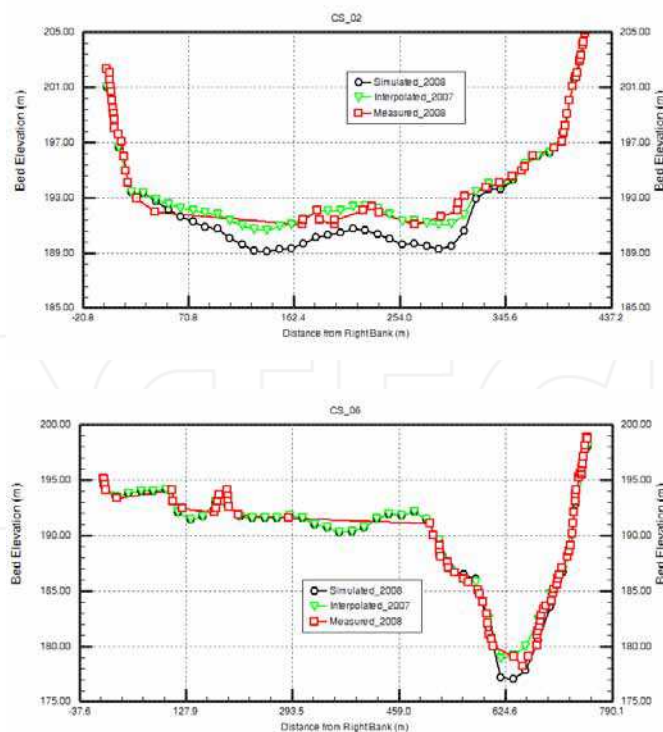


Fig. 19. Location of cross sections



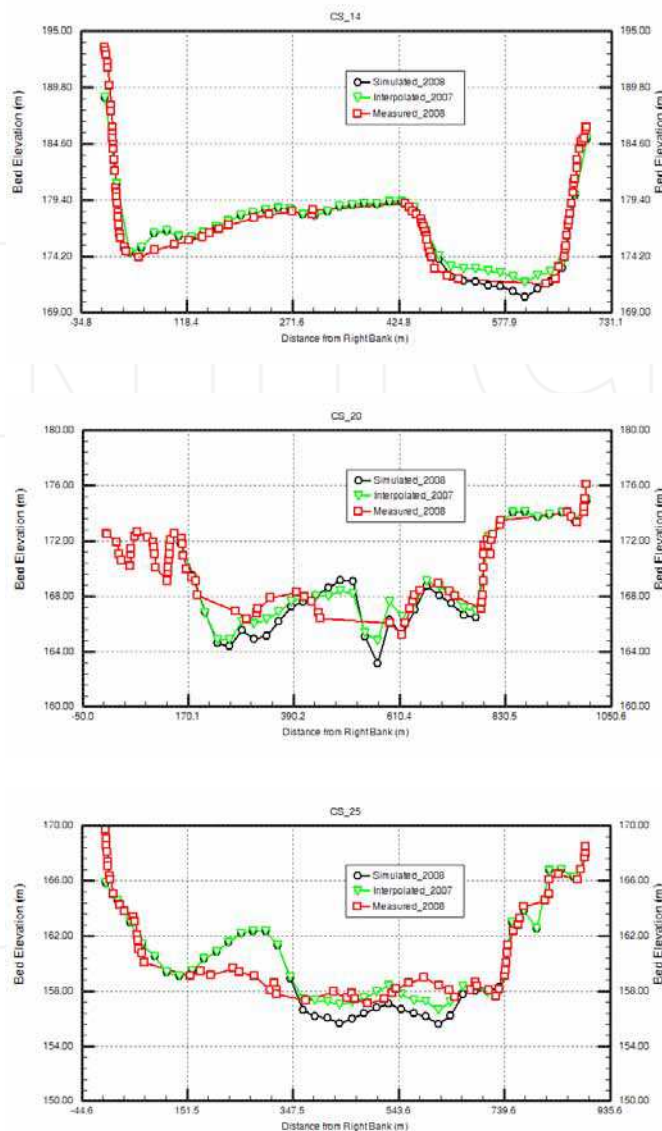


Fig. 20. Comparisons of the bed measured and computed cross-sections

5. Conclusions

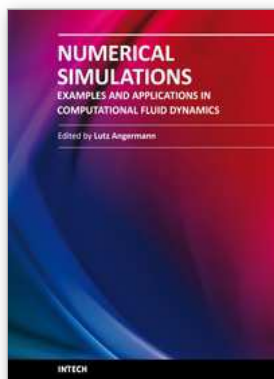
The CCHE2D model was used to simulate the sediment transport and the bed morphological changes in the upstream and downstream reach of Chi-Chi Weir in Choshui River, Taiwan. The model has been modified to handle the bedrock erosion which was

feasible and applicable to the field engineering problem. Following conclusions are made according to the analysis of simulated results and measurements:

- Morphological changes occurred mainly during big flood events. Erosions are near the inlet and in front of the Weir. More depositions are distributed in the lower part of the reservoir, and near the right (north) bank.
- The model has been modified to handle the bedrock erosion and representing different erosion control structures. The bedrock erosion formula was modified to be feasible and applicable to the field engineering problem.
- Generally, the trend of the simulated bed change agreed with the observed pattern, but differences remain obviously. In the case of upstream Chi-Chi Weir, the model under-predicted a large scour hole close to the Weir and large erosions over the delta which are partially affected by the unknown amount of dredging. The scour hole in front of the Weir could be due to the three dimensionality of the flow and sediment transport, which could be solved better with a 3D model.
- The CCHE2D model is capable of simulating sediment transport and morphological changes within the study reach with unsteady boundary conditions for the flow and sediment. The wetting and drying treatment technique of the model makes simulations with complex morphology very efficient.
- The uncertainty of the data such as channel bed topography, sediment load, its composition and bed material composition may affect the prediction accuracy of the numerical model.

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